AR-008-868

DEPARTMENT OF DEFENCE

DSTO

Electronic Warfare Division

ELECTRONICS RESEARCH LABORATORY

RESEARCH REPORT
ERL-0827-RR

IN-FIBRE BRAGG GRATINGS FOR MILLIMETRE-WAVE EW SYSTEMS (U)

by

Anthony C. Lindsay

APPROVED FOR PUBLIC RELEASE

UNCLASSIFIED

AR-008-868

DSTO
AUSTRALIA

ELECTRONICS RESEARCH LABORATORY

Electronic Warfare Division

RESEARCH REPORT
ERL-0827-RR

IN-FIBRE BRAGG GRATINGS FOR MILLIMETRE-WAVE EW SYSTEMS

by

Anthony C. Lindsay

SUMMARY

Fibre-optic microwave and millimetre wave systems technology has matured rapidly over the last few years. The report examines some possibilities for very wide bandwidth signal distribution and analysis based on in-fibre Bragg gratings. The gratings are fabricated within the core and become an integral property of the optical fibre material.

MARCH 1994

APPROVED FOR PUBLIC RELEASE

POSTAL ADDRESS: Director, Electronics Research Laboratory, PO Box 1500, Salisbury, South Australia, 5108. ERL-0827-RR

UNCLASSIFIED

CONTENTS

FIGURES

THIS PAGE INTENTIONALLY BLANK

1 INTRODUCTION

The potential for the exploitation of many types of photonic techniques in the field of Electronic Warfare (EW) has long been appreciated. It is only relatively recently however that the technology has matured to the degree that the massive bandwidths intrinsic to photonics are able to be realised in viable concept demonstrator systems.

In particular, guided-wave photonics (the fields of integrated optics and fibre optics), offers great potential for the development of new EW systems. Guided-wave photonics technology has reached the stage where components such as fibre optic delay lines and recirculators can be constructed that have acceptable insertion loss, good sensitivity and reasonable dynamic range.

In most applications however, the fibre link is treated simply as another type of waveguide, useful for piping large bandwidths from point to point. This task is of course extremely useful, and can of itself be beneficial in such areas as the construction of remote microwave links and in delay line signal processing architectures (e.g. transversal filters). However the full potential of guided-wave photonics technology will not be realised until the optical medium *itself* is configured to undertake some signal processing applications. In particular, there are significant advantages that accrue if the signal processing configuration leads directly to a frequency domain output from the fibre rather than a time domain signal. These advantages include:

(a) a reduction in the bandwidth of the detection electronics, since the bandwidth is now determined by such factors as rf pulse durations and acceptable detection times, rather than signal carrier frequency,

(b) a related reduction in the noise floor and improved sensitivity due to the smaller detection bandwidths, and

(c) a reduction in system cost and a potential increase in system performance associated with points (a) and (b).

One new technique for frequency domain processing involves using ultraviolet laser light to write phase gratings directly into the core of germanosilicate optical fibres. This report describes the current techniques for constructing in-fibre gratings, their principle of operation and proposes a number of applications for new photonics-based EW systems.

2 IN-FIBRE BRAGG GRATINGS - MANUFACTURE AND PHYSICAL PROPERTIES

It was discovered in 1978 [1] that permanent, periodic refractive index changes can be induced in germania-doped silica optical fibres by exposure to intense ultra-violet (uv) radiation. The perturbations are typically recorded into the fibre core by means of two intersecting, coherent uv lasers (excimer pumped dye, doubled argon-ion or quadrupled Nd:YAG) as shown in Figure 1. The exact physical mechanism of the formation of the periodic phase grating is not yet fully understood. It is probably the result of charge migration from oxygen vacancy defect sites in the regions of high optical intensity, with subsequent trapping of the charged carriers at defect sites located in regions of low optical intensity [2]. This results in a built-in, permanent electric field in the fibre core which in turn leads to a small, periodic refractive index change via the photorefractive effect. Another possible formation mechanism [3] involves stress-relaxation associated with bond breaking at the oxygen vacancy defect site, thereby causing a refractive index perturbation via the elasto-optic effect (the same effect by which acousto-optic Bragg cells operate). Typical refractive index changes are less than 5×10^{-4}, however this is sufficient to manufacture gratings which exhibit 99% reflectivity at the grating peak [2]. The gratings are usually of the order of 10 mm long and have a bandwidth of the order of 0.1 nm at a centre frequency of 1550 nm.

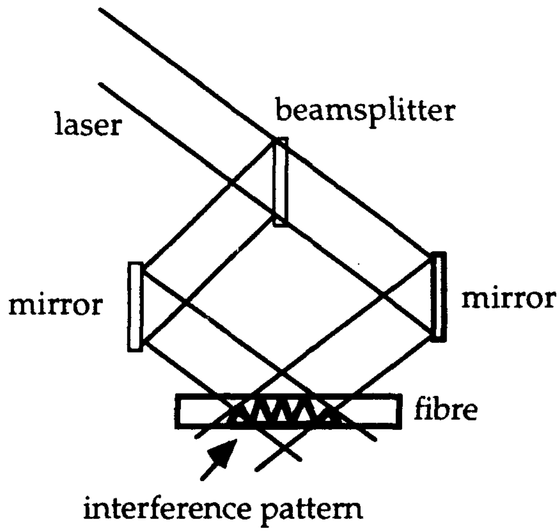

Figure 1 Formation of a periodic phase grating by the interference of uv laser beams.

It is clear that the periodicity of the grating can be tuned by varying the angle of intersection θ between the interfering beams, and hence the centre frequency of the grating can be simply and accurately altered as required. The intensity variation for two interfering, co-polarised beams of wavelength λ is proportional to

$$I(x) \propto 1 + \cos\left[\frac{4\pi \sin\theta}{\lambda} x\right] \tag{1}$$

Thus, the periodicity of the grating as a function of x - the distance along the fibre - is controlled by the sine term. Another important feature of the gratings is their environmental stability. Research has indicated that the grating reflectivity remains unchanged for temperatures as high as 250 °C [4], with total erasure of the grating not occurring until a temperature of about 900 °C is reached. The grating periodicity will vary linearly with temperature as a result of both thermal expansion of the fibre and the change in refractive index due to temperature (the thermo-optic effect). The change is given by [4]

$$\frac{\delta\lambda}{\lambda} = (\alpha + \xi)\,\Delta T \tag{2}$$

where α is the thermal expansion coefficient and ξ is the thermo-optic coefficient. A typical value for the total coefficient is of the order of $10^{-5}/^{\circ}C$, as shown in Figure 2 [4]. The thermal stability of the gratings means that once written they essentially become a permanent feature of the fundamental structure of the fibre core. Short term relaxation-type behaviour of the gratings can be compensated during the manufacturing process by annealing the fibre at about 100 °C, to ensure that the structure is stable at typical operational temperatures.

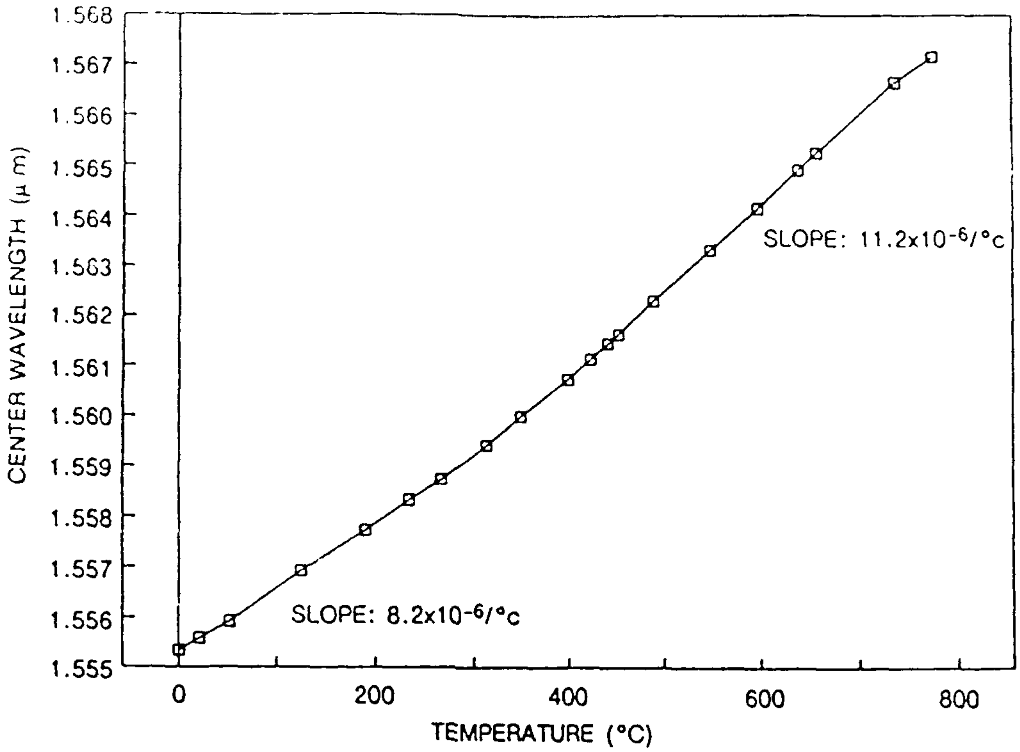

Figure 2 Change in grating resonance as a function of temperature [4].

These gratings can then be spliced into guided wave photonics architectures for EW signal processing.

The fibre gratings can not only be used in a reflective mode, but can also be used to rotate the polarisation of the spectral components of the transmitted beam that lie in the passband of the grating structure. This mode of operation also has obvious applications for signal processing, and indeed the architectures are potentially easier to implement. However, the technique is much less developed than the simple reflective grating mode of use, and as such this report concentrates solely on using reflective in-fibre gratings for signal processing applications.

3 SOME APPLICATIONS OF IN-FIBRE BRAGG GRATINGS

In this section a number of potential applications for in-fibre gratings are outlined. In particular a combination of several different photonics technologies will be described in order to achieve:

(a) the automatic routing of photonic millimetre wave local oscillator signals, and

(b) the construction of extremely wideband, all-optical millimetre wave spectrum analysers

3.1 Spectral Properties of Gratings

The potential utility of fibre gratings for rf signal processing can be seen by considering a number of features of the devices. For example, the achievable bandwidth of these devices using the interferometric fabrication technique is ~0.1 nm at a central wavelength of 1500 nm (the favoured long-distance optical telecommunications wavelength). Since $c=\lambda f$ it follows that in general the spectral bandwidth and frequency bandwidth are related via

$$\left|\frac{\Delta\lambda}{\lambda}\right| = \left|\frac{\Delta f}{f}\right| \tag{3}$$

All of the papers in this field naturally quote their results in terms of spectral bandwidth, however for the applications in mind the relevant quantity is frequency bandwidth, and as such the appropriate relationship is

$$|\Delta f| = \left|\frac{c\Delta\lambda}{\lambda^2}\right| \tag{4}$$

where Δf is the frequency width of the grating. It is apparent that the current frequency widths of the gratings are about 10 GHz. This width is sufficient for applications such as millimetre wave local oscillator distribution or coarse frequency determination in a millimetre wave receiver. If the gratings are made longer, this width can be narrowed to the gigahertz or even to the tens to hundreds of megahertz region. This then allows the possibility for signal analysis applications that require much finer frequency determination. Another alternative is to use of a pair of wide-band gratings in a fibre Fabry-Perot geometry, which can lead to megahertz passbands - this option will be discussed further in Section 3.4.

The option of increasing the fibre grating length for higher frequency resolution may be achieved by a new method of using standard photolithographic or electron beam direct-write techniques to define a mask which has the grating etched onto it, then using a *single* uv source to write the grating into the fibre through the mask. This technique has the advantage that it is potentially much more robust than the interferometric technique, which by its very nature is environmentally sensitive. Also, due to the relaxation of fabrication tolerances, the yield for the production of usable gratings would be very significantly enhanced. It is clear that sub-micron technology would be ideal for this application, and hence the facilities of the proposed nanostructure fabrication centre could be of importance in manufacturing these long, high resolution gratings.

Also of importance is the fact that the frequency response of the grating is simply the Fourier transform of the spatial grating distribution. This means that the grating can be apodised along its length in order to reduce the sidelobes of the spectral response. Such a tailored grating response is shown in Figure 3 [2], where the effect of a Gaussian apodisation characteristic is reflected in the almost Gaussian spectral response of the filter (Figure 3 is a measurement made on an actual device and not a theoretical calculation, which also demonstrates that spectral tailoring is experimentally realisable). Spectral tailoring of the grating can also be used to enable wide bandwidth frequency determination as shall be discussed in Section 3.2.

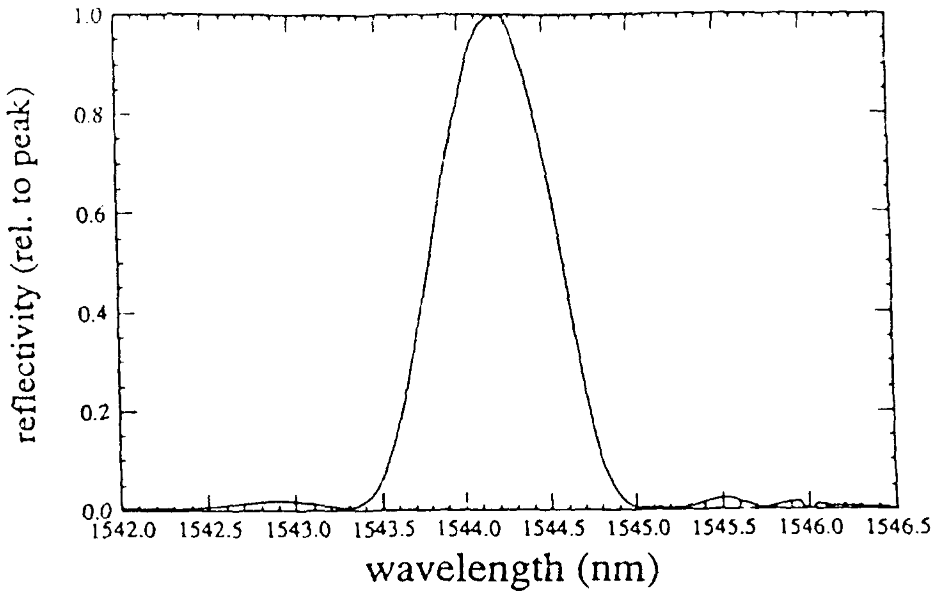

Figure 3 Response of a grating with Gaussian apodisation of uv writing beams [2].

3.2 Millimetre Wave Local Oscillator Distribution

A major problem associated with very wide bandwidth millimetre wave signal detection is the efficient generation and distribution of millimetre wave local oscillators suitable for down-converting the raw signals to a baseband for capture and subsequent analysis using conventional microwave technology. A potential solution to this problem is to use two highly stable, frequency tunable laser sources which are slightly detuned such that the required millimetre wave signal is the beat frequency between the two lasers. By mixing the lasers on a fast photodiode, the millimetre wave beat signal is recovered, amplified and can then be used for the LO of the millimetre wave mixer.

It is straight forward to show that the available LO power from the detector is given by [5]

$$P_m = \alpha r^2 P_1 P_2 R_L \quad (5)$$

where P_1 and P_2 are the optical powers of the laser sources, α accounts for all optical loss contributions including fibre link loss and coupling loss of the fibre to the detector, r is the detector responsivity (mA/mW) and R_L is the total impedance of the load seen by the photodiode.

Commercial systems based on locking two diode pumped, monolithic ring YAG lasers are available that allow accurate and tunable locking at frequencies from 1 to 100 GHz [6]. The frequency resolution is less than 1 kHz, the stability about 100 ppm and the phase noise at 100 MHz and 1 kHz from the carrier is better than -60 dBc/Hz. Up to 150 mW of optical power can be coupled into the delivery fibre, however in practice the actual system powers will be determined by the power handling capability of the millimetre-wave photodiode detectors.

Despite the extremely large bandwidth capability of the photonic LO generation technique, in a millimetre wave ESM system the detection will still have to be undertaken in bands due to the finite bandwidth of the electronic components of such systems. This means that the LO signal will need some form of switchable distribution network. It is proposed that in-fibre gratings would be ideal for such purposes.

The basic st-·.ture from which an optical fibre distribution network may be constructed is shown in Figure 4. It is a fibre Mach-Zehnder interferometer constructed from two fused taper 3-dB directional couplers. A distributed Bragg grating reflector is written into each arm. The laser light initially enters the input port labelled a, and is uniformly split into each arm of the interferometer. If the laser wavelength falls within the passband of the Bragg gratings, the light will be reflected back towards the input coupler. If the propagation paths are identical, upon reaching the input coupler coherent recombination will occur such that all of the light exits port b. Thus, the fibre Mach-Zehnder acts as a wavelength-selective tap [7].

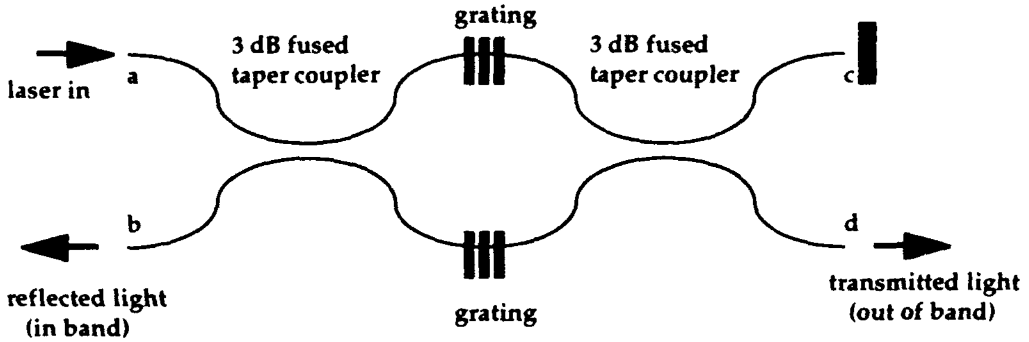

Figure 4 Mach-Zehnder wavelength-selective tap.

This basic configuration can be used to construct an all optical, millimetre wave distribution network as shown in Figure 5.

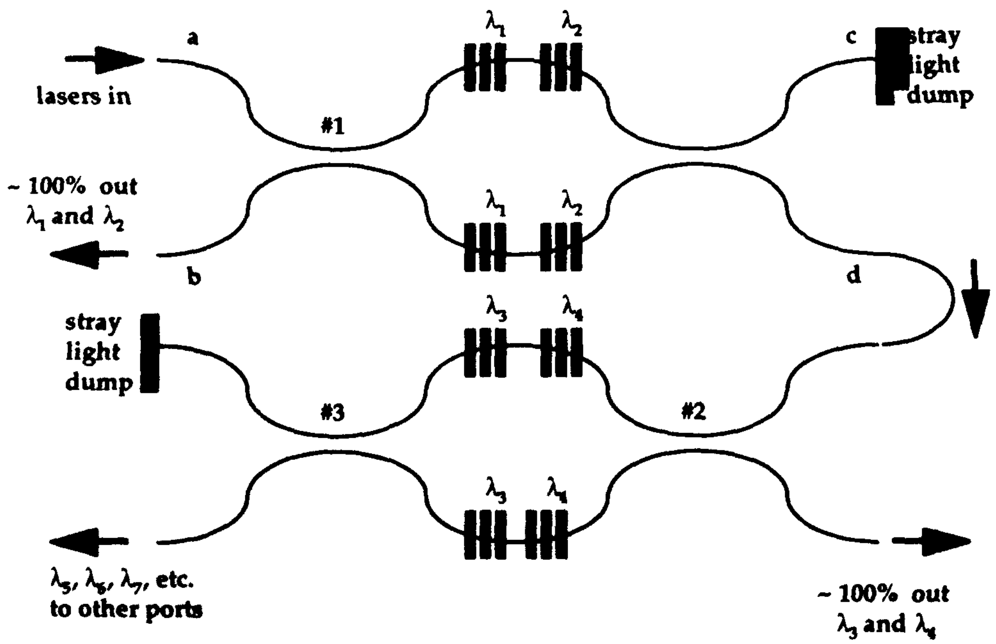

Figure 5 Passive distribution network for mm-wave LO signal.

The distribution network would consist of a number of sections each of which has two fibre gratings. Each grating is tuned to a different centre wavelength, with the wavelength difference satisfying

$$\Omega_i = 2\pi cn\left(\frac{1}{\lambda_{1,i}} - \frac{1}{\lambda_{2,i}}\right) \tag{6}$$

where Ω_i is the required LO beat frequency for band i. As long as the optical distance travelled along each arm is such that there is no net phase shift (i.e. $\Delta\phi=2m\pi$; m=0, 1, 2,..), all of the reflected energy will couple back out through port b of the 3 dB coupler [7]. When the lasers are tuned to non-resonant wavelengths for coupler #1, the light will simply pass through the grating with minimal perturbation and 100% coupling occurs through port d (again, the path lengths must be tailored such that there is no net phase shift at the coupler). Despite the interferometric nature of the coupling processes, the fabrication should be reasonably straight forward since the path lengths along each arm can be trimmed by non-interferometric uv exposure, which increases the refractive index uniformly along a fibre section and thereby changes the relative phase at which the light recombines at the input and output couplers. The coupling ratios can be monitored during the trimming stage of manufacturing and thus the fairly stringent tolerances on optical path lengths should be attainable in a straight-forward manner.

An arrangement such as shown in Figure 5 ensures that the required beat frequency is eventually coupled out at the appropriate port, since the laser wavelengths are chosen such that the LO beat frequency is that required for the band to which the light will be delivered. In this manner a totally passive architecture for the self-routing of millimetre wave local oscillator signals can be realised. Backscattered light (due to imperfections) that arrives at the wrong band will have a beat frequency outside the response of the electronics at that band and so will not effect the performance of the system (there must be, of course, be high quality optical isolators in front of each of the lasers).

The LO signal can be distributed to one band at a time by tuning the lasers, or a number of bands can be fed simultaneously by using gratings with less than 100% reflectivity and several laser sources. The idea is shown in Figure 6, where four lasers can be used to supply local oscillators to five different bands. This option could be particularly useful in future systems that can exploit the full 50 GHz bandwidth that has been demonstrated in optical modulators [8], since only three laser sources would be necessary to cover the region of 1 GHz to 110 GHz.

An alternative, less elegant architecture is shown in Figure 7.

This architecture will achieve the same LO distribution as in Figure 5. The couplers are now assumed to be polarisation dependent (i.e. polarisation splitters). The Faraday rotator is a non-reciprocal device that rotates the forward wave by 45°, and the reflected wave by a further 45° in the *same* direction, thereby causing 100% coupling of the now orthogonally polarised reflected wave out of port b. The half-wave plate is a reciprocal device which simply rotates the plane of polarisation of the transmitted wave back to the original plane. As can be seen, this architecture may be quite polarisation sensitive, whereas the first architecture is only sensitive to *differential* variations in the polarisation state that occur in the short sections of each of the interferometer arms. The architecture incorporating the Faraday rotators is undoubtably much easier to construct. In fact the combination of polarisation dependent coupler plus Faraday rotator constitutes the optical equivalent of a microwave circulator, and pre-packaged devices are commercially available.

An alternative technique to construct the isolator may be to replace the Faraday rotator with a fibre quarter-wave plate (assuming that the chirality of circular polarisation of the forward propagating wave is reversed by reflection from the phase grating and that the small birefringence associated with the grating does not significantly perturb the final polarisation state). If this is the case, then the effect of a double pass through the quarter-wave plate with a reflection in between will result in the backscattered signal again being orthogonally polarised at the polarisation splitter, 100% of the reflected light will couple out of port b, and use of the relatively expensive Faraday rotator can be avoided. Quarter-wave and half-wave "plates" can be constructed simply by having a number of loops in the fibre of the appropriate diameter and relative orientation.

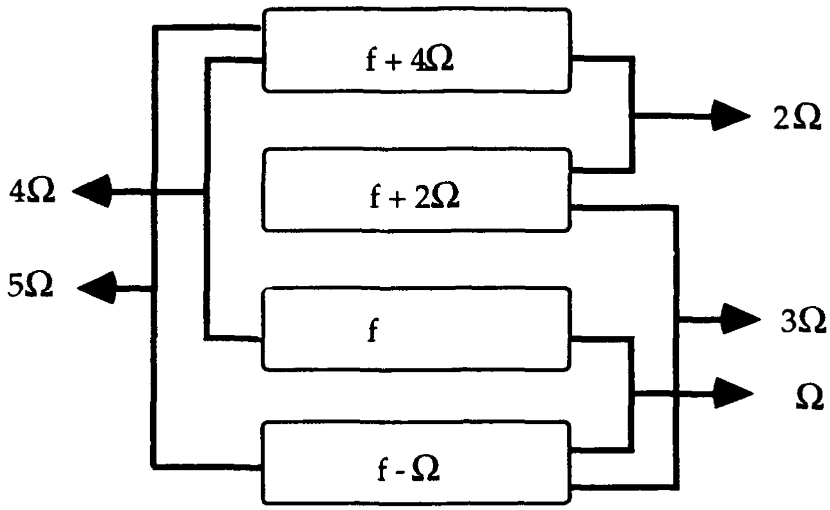

Figure 6 Distribution of local oscillator signals to several different bands.

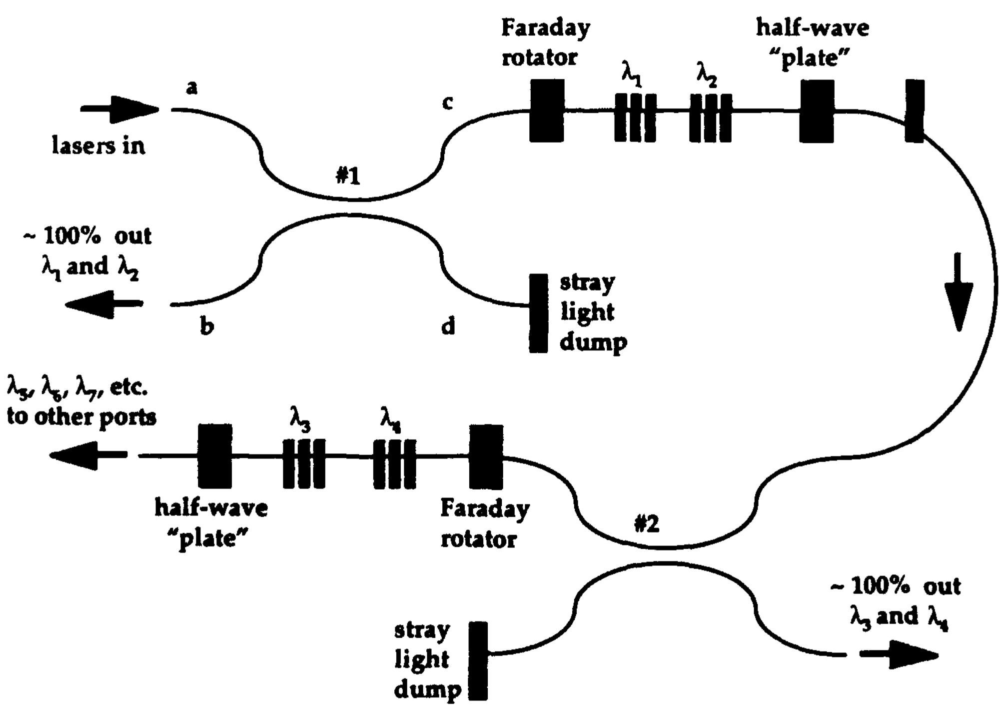

Figure 7 Alternative architecture for photonic mm-wave local oscillator distribution.

3.3 Frequency Determination Using Tailored Filters

Another potential application for in-fibre gratings is for the determination of the frequency of unknown millimetre wave signals. One option is to exploit the property that the spectral response of the grating is simply the Fourier transform of the envelope of the spatial distribution of the refractive index variation. As demonstrated in Figure 3 [2], a Gaussian apodisation of the grating (achieved simply by masking the uv light) has resulted in a Gaussian-shaped spectral response with low sidelobes (the residual sidelobes probably arise due to spectral chirp of the grating, in which the effective grating period varies with refractive index, and so the more highly exposed regions tend to have a slightly different resonance frequency than the less exposed regions. It should be possible to compensate for this effect). Thus the possibility arises of constructing well behaved, totally passive and environmentally robust filters covering very wide millimetre wave bandwidths.

If a highly stable, narrow linewidth laser is phase modulated at millimetre wave frequencies, the modulation will result in Bessel function sidebands just as for any other electromagnetic carrier (it is possible to have an AM modulated photonic carrier, however for reasons discussed in section four phase modulation of the carrier is assumed). The amplitude of the sidebands is dependent upon the power of the modulating signal and the characteristics of the rf→optical transducer. These considerations are dealt with in section four. Given that sidebands are generated, the idea would simply be to use a grating that has been tailored to have a different characteristic spectral response on either side of the carrier, and then use a technique of amplitude comparison of the first order sidebands to determine the modulation frequency. This is shown schematically in Figure 8.

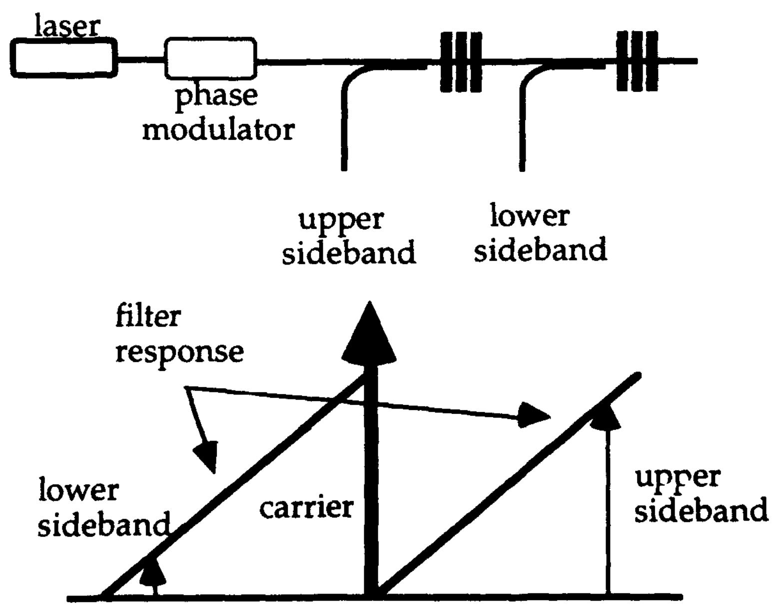

Figure 8 Frequency determination by sideband amplitude comparison.

The frequency responses do not have to be linear - only monotonic with frequency across the bandwidth of interest. As an example, even for the case of the relatively wide (~1 nm) Gaussian spectral response shown in Figure 3, the reflectivity at the half maximum height changes at a rate of about 1.5% per gigahertz which, depending upon the amount of power in the sidebands, may be enough to determine frequencies at the gigahertz level. Non-linearity can be handled simply by having a look-up table. This architecture would require a narrow-band rejection filter at the carrier frequency, which could be realised by having a long, high reflectivity phase grating in the optical line prior to the tailored filters. Alternatively, by detuning the optical carrier wavelength so that the carrier is not reflected, and having two filters with different tailored frequency responses, it may be possible to again use amplitude comparison of the sideband amplitudes reflected by each filter to uniquely determine the modulating frequency.

A limitation of this architecture is that it can handle only one input signal at a time, however at the frequencies for which it is intended (>30 GHz) the assumption of only having a single emitter present at any time is probably reasonable.

3.4 Frequency Determination Using Narrowband Gratings

A second possible implementation using grating architectures is to build a channelised receiver based on narrow band filters. The narrow band filters can be constructed by fabricating a long grating via the masking technique described previously.

A number of narrow band gratings can be configured together to act as a frequency channeliser, with one possible architecture shown in Figure 9. Again, the carrier is phase modulated and the device relies on channelising and detecting power at the sideband frequencies. To increase the sensitivity, light in both the upper and lower sidebands can be detected on the same photodiode (the photodiode is envisaged to have only a ten megahertz or significantly less response time and so the beat between the sidebands is averaged out). A number of gratings can be fabricated one after the other, and as such the device can act effectively as a channelised receiver. Important differences between this architecture and standard electronic channelising are:

(a) the device is very wide bandwidth (clearly most suited to millimetre wave applications) with the filter responses and signal being unaffected by parasitics, EM interference etc.

(b) the device does not spread the available energy out to a set of lossy filters. In contrast, as with the self-routing local oscillator described in Section 3.1, all of the energy appears at the appropriate channel. This has the important consequence that as many channels as required can be cascaded one after the other with only the usual very small optical propagation losses limiting the overall device performance.

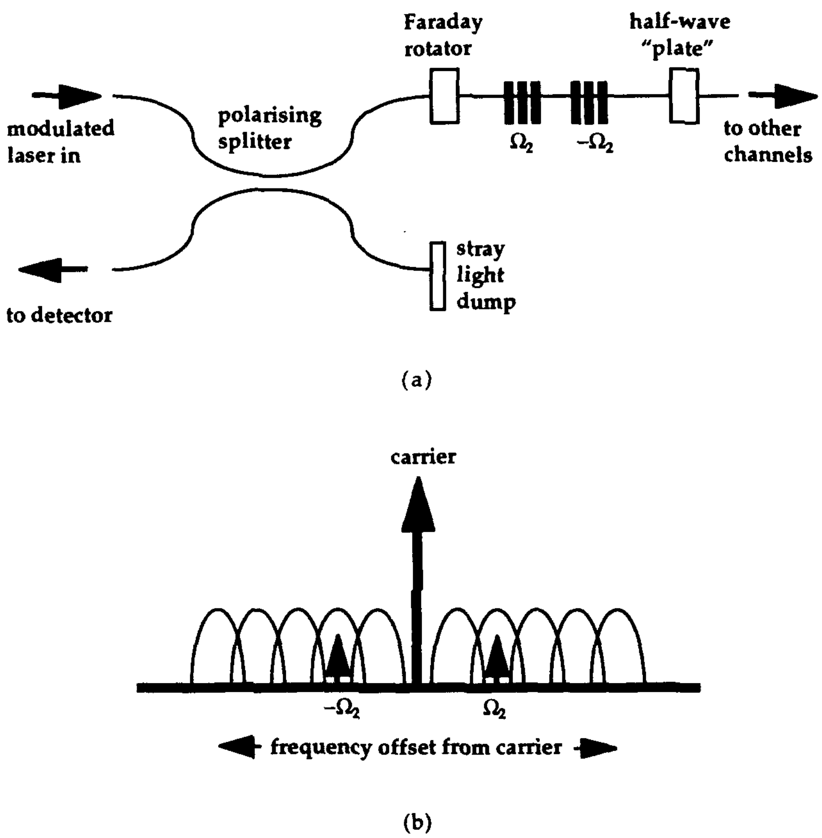

Figure 9 Optical channeliser using narrow band fibre gratings. In (a) the building block for the architecture is shown, (b) illustrates the passbands in frequency space.

An alternative to adding both sidebands together to maximise sensitivity would be to have different sets of bandpass filters for both the upper and lower sidebands. By organising a slight frequency offset between the two sets, the channelisation itself would provide a coarse frequency estimate, and then an additional amplitude comparison circuit as discussed in the previous section could be used to refine the estimate.

3.5 Frequency Determination Using In-Fibre Fabry-Perot Filters

Fine frequency resolution can also be achieved without the use of intrinsically narrow band filters by combining two moderate bandwidth gratings in-line to form an in-fibre Fabry-Perot interferometer. The Fabry-Perot is a multipath interferometer with two high reflectivity mirrors (the gratings) which exhibits very narrow transmission fringes in the reflection band of the grating pair. The transmission is periodic with a period (in frequency space) inversely proportional to the distance between the gratings. Figure 10 [2] shows the results obtained from such a fibre Fabry-Perot. The narrowest transmission fringe is only 1.6 MHz wide. As can be seen from Figure 10, it is possible to scan the filter over tens of gigahertz by varying the optical path length between the gratings that form the interferometer. This can be done by changing the refractive index of the fibre between the gratings, either electro-optically or, as in the case of Figure 10, by application of a strain on the fibre.

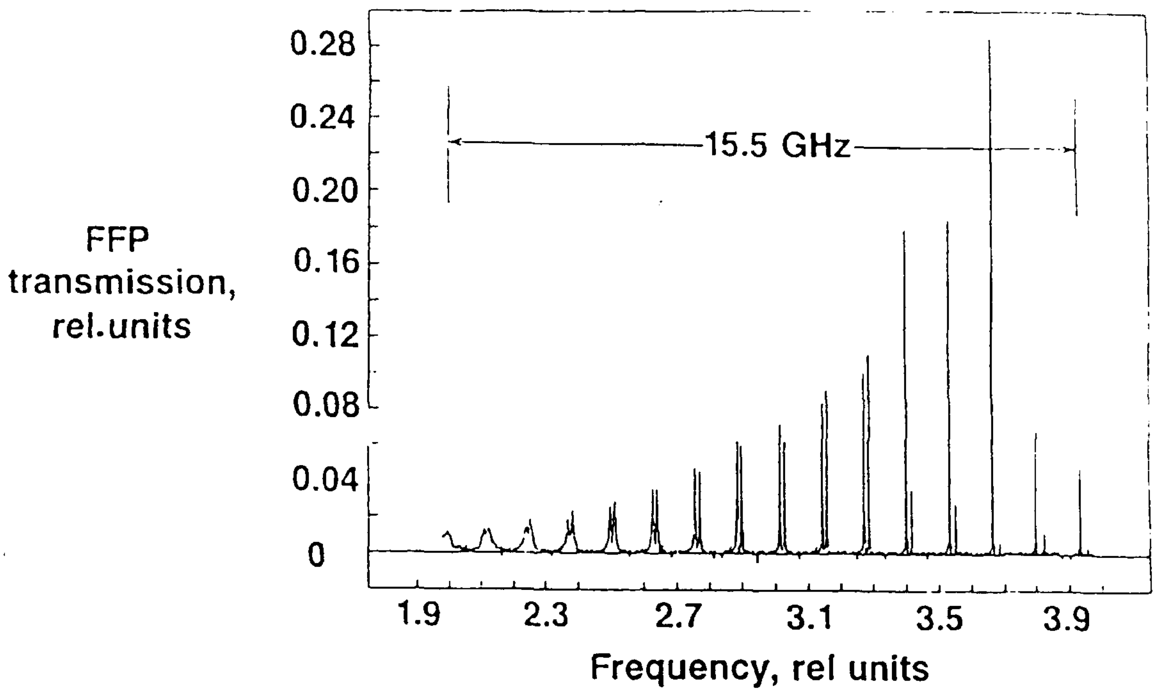

Figure 10 **Narrowband fibre Fabry-Perot response. The double fringe structure can be eliminated using polarised light. The grating is tuned by stretching the fibre [2].**

Possible high resolution signal processing architectures that use moderate bandwidth in-fibre gratings are shown in Figure 11. In Figure 11a, the first grating acts as a coarse channeliser with the subsequent Fabry-Perot filters acting as fine channelisers. Each arm of the fine channelising section will have a Fabry-Perot filter that has its maximum fixed to a slightly different frequency. The width of the frequency bins will be determined by considerations such as the required resolution, the amount of optical power available to spread among the high resolution channels etc. The architecture of Figure 11b employs coarse channelisation followed by a high resolution scanning Fabry-Perot filter. This is the optical analogue of a coarse frequency channeliser with *each* channel terminated by a scanning superhet. The coarse channeliser will allow an instantaneous coarse frequency measurement, with the superhet providing subsequent fine resolution and frequency discrimination between simultaneous signals that fall in the coarse channeliser passband. The architecture shown in Figure 11c would probably be the most useful implementation. The coarse channelisation is done by the grating sequence, with the frequency estimate of selected signals being passed on to the tunable in-fibre grating. The optical signal in the high resolution arm of the system is delayed so that the in-fibre scanning Fabry-Perot can be pre-set to scan the frequency regime of interest prior to the arrival of the signal.

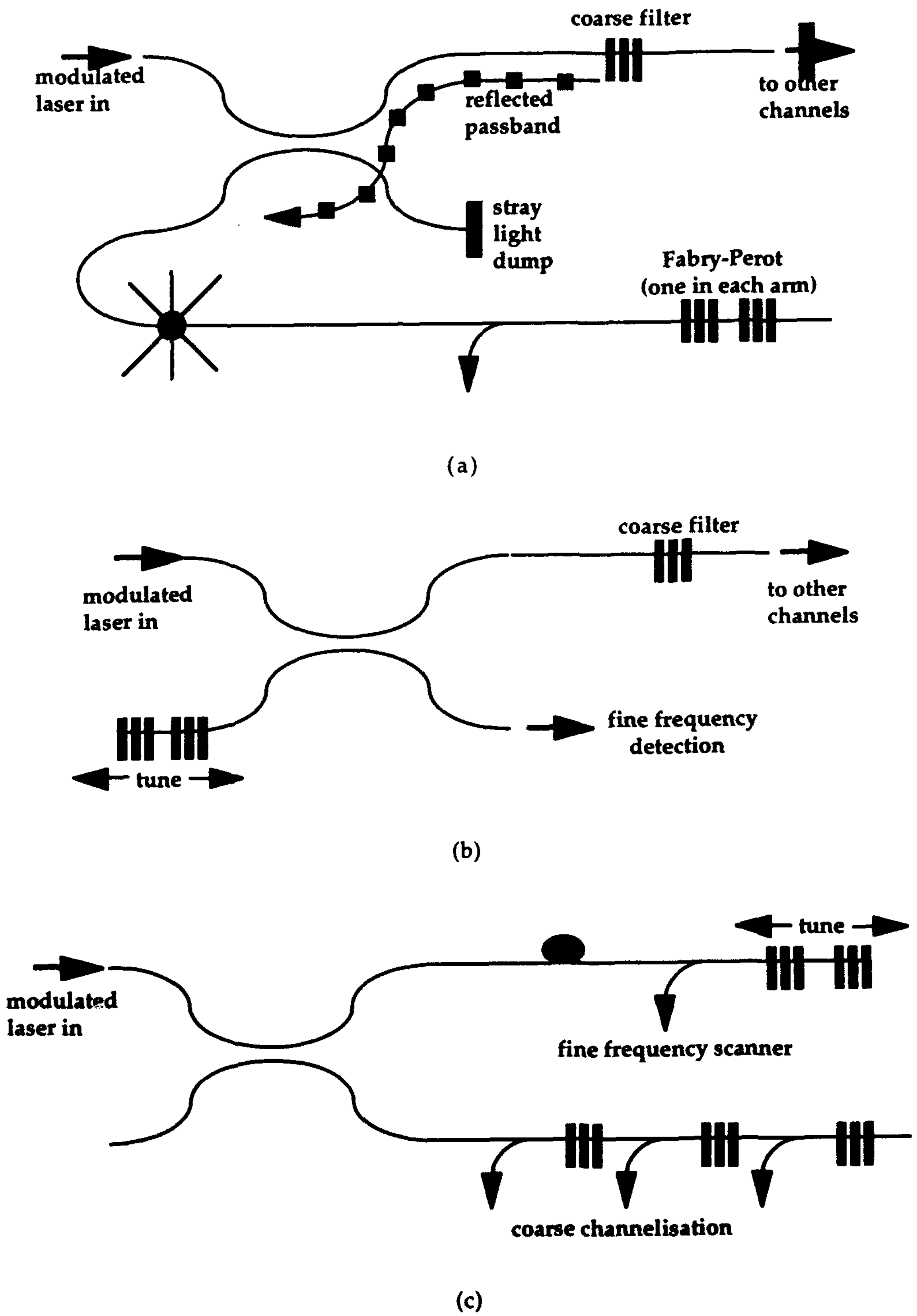

Figure 11 Various architectures for obtaining fine frequency resolution used wideband gratings. The polarisation controlling components are not shown.

4 SYSTEM CONSIDERATIONS

The modulation technique used to impress the millimetre wave signal onto the laser carrier will determine the optical spectrum of the laser light. Electroabsorption or reflection modulators will basically result in the single upper and lower sidebands associated with amplitude modulation (although there will necessarily be an associated phase modulation due to the Kramers-Kronig relation between the real and imaginary parts of the dielectric permittivity of the modulator). Interferometric and directional coupler intensity modulators rely on pure phase modulation of the underlying photonic carrier, and as such the sideband structure will be a Bessel function comb. Since the latter modulators are the most popular and are commercially available, an analysis based on a phase modulated photonic carrier will be used.

The optical signal emerging from an electrooptic phase modulator can be written as

$$E_{out}(t) = E_o \cos[\Omega t + \delta \sin \omega t] \tag{7}$$

where

$$\delta = \frac{n_z^3 r_{33} \Omega V_{in} L}{2cG} = \frac{\pi V_{in}}{V_\pi} \tag{8}$$

The quantity δ is the modulation index, which is determined by the input voltage V_{in} and the modulator parameters: refractive index n_z, electro-optic coefficient r_{33}, optical frequency Ω, electrode length L and the overlap integral G. For a commercially purchased modulator, the device dependent quantities are lumped together by a parameter which describes the actual measured voltage that achieves a π phase shift of the carrier, the quantity V_π.

It is straight forward to expand equation (7) to show that the optical power in the nth sideband due to a modulation index δ is just

$$P_n = \alpha P_{out} J_n^2(\delta) \tag{9}$$

where P_{out} is the optical power output from the modulator, $J_n(\delta)$ is the nth order Bessel function and α accounts for loss of optical intensity due to fibre attenuation, coupling to the detectors etc.

The sensitivity of the detectors will be determined by either the thermal noise floor, stray light intensity or the detector dark current since, with the fibre grating techniques outlined in Section 3, essentially *no* laser light at the carrier frequency is present at the detectors in the absence of an rf signal. This is in contrast to a normal fibre optic microwave link, where the detector is always subject to at least half of the available optical power in the link. This lack of an unwanted dc signal component means that very high gain detectors such as avalanche photodiodes can be used to maximise the sensitivity of the system. The thermal noise floor limitation is

$$kT = -174 \text{ dBm/Hz} \tag{10}$$

which for a 50 Ω load, a 10 MHz detection bandwidth and a responsivity of 0.8 for the detector corresponds to an optical power in the sidebands of the order of -42 dBm. This rough estimate for the attainable sensitivity of systems that rely on detecting the sideband energy of a phase modulated laser is consistent with actual manufacturers specifications. For example, the Lasertron QDFB-010 pinFET receiver module incorporates an AGC circuit to obtain a sensitivity of -52 dBm (optical) and a dynamic range of 47 dB [9]. Detectors with internal gain such as avalanche photodiodes could improve this sensitivity by 10 dB or so. The ultimate limitation in detection would conceivably be achieved by going to single photon counting systems. At this level dark counts of ~40 photons per second are achievable [10], and as such if tens or hundreds of photons were counted in a typical rf pulse duration (e.g. 1 microsecond), then this would indicate a valid sideband detection. One hundred, 1.3 μm photons arriving in a one microsecond period corresponds to an optical power in the sideband of only ~ -78 dBm. The option of having single photon counting systems on each output of a channeliser may be very expensive, however the example demonstrates that very high optical sensitivities can be achieved in principal. Developments such as commercially available SPADs (single photon avalanche diodes) will significantly reduce the cost of implementing photon counting options and hence realise the potential for high sensitivity systems. In practice, the sensitivity will probably be limited by spurious stray light in the fibre.

The optical power in the sidebands is related to the input rf power by Equation (8) and Equation (9). If typical modulator parameters are assumed (i.e V_{π} = 12 V and a modulator optical loss of $\alpha \sim 4$ dB), then the minimum detectable rf power is about -40 dBm, assuming that the commercially available QDFB-010 pinFET receiver is used as the detector and ~50 mW of optical power is initially coupled into the modulator. At the extreme limit of employing photon counting detection systems as described previously, the example of -78 dBm (optical) sensitivity (i.e. using 100 photons/microsecond as the minimum detectable signal) corresponds to an rf sensitivity of about -60 dBm.

The sensitivity limits presented represent those achievable using both standard p-i-n detector technology and the most sensitive detection technologies available. Thus it would be reasonable to assume sensitivities somewhere between these figures may be achievable in practice, with the figures varying depending upon the architecture used to implement the system. Increases in the sensitivity can obviously be obtained by lowering the modulator V_{π}, increasing the optical input power, using HEMT technology to provide wideband millimetre wave preamplification etc.

The dynamic range will be limited by the generation of higher order intermods and harmonics due to the non-linear nature of phase modulation. In a millimetre wave system with the expectation of only one signal being present at any given time, the dynamic range is determined when the $J_2(\delta)$ Bessel function (describing the amplitude of the second harmonic) reaches the sensitivity threshold. In the case of the pinFET receiver this occurs at an rf input power of about 0 dBm, indicating a dynamic range of only 40 dB. Fortunately, channelised receiver architectures lend themselves to relatively straight-forward handling of the detection of spurious harmonics, especially in the low emitter density scenario, and as such the actual usable dynamic range may be somewhat enhanced. The possibility of using electroabsorption or reflection modulators that provide AM modulation with the benefit of minimal higher order harmonics would also lead to improved dynamic range. Finally, the use of in-fibre, all-optical amplification (suitably filtered) may present a possibility of significantly enhancing system sensitivity.

The previous calculation is based upon the most stringent detection scenario, where the response of the system is capable of signal discrimination on a pulse-to-pulse basis. In a low emitter density environment and with a channelised architecture where it may be expected that even simultaneous signals will fall into different frequency "bins", the sub-microsecond system responses may not be required.

Existing architectures based on this much less restrictive assumption have detector integration times of the order of ten milliseconds to hundreds of seconds. If a detector integration time of 10 seconds is assumed, the detectable optical power in the sidebands is now enhanced to about -82 dBm (optical), which corresponds to an input signal sensitivity of the order of -60 dBm (as for the photon-counting examples above). A number of points should be stressed regarding this result:

a. because of the channelised architecture, the detection bandwidth is determined by the integrated optical modulator. The best commercially available modulator has an rf bandwidth of 52 GHz, and as such this signal detection architecture holds the promise of -60 dBm sensitivity across an "instantaneous" 50 GHz detection bandwidth.

b. the sensitivity calculations relate to rf power *into the modulator*. There is *no* assumption of rf pre-amplification or antenna gain. If the device is directly mounted to a directional horn antenna with, say, 10 dB gain, then the system sensitivity would improve to -70 dBm for a 10 second detector integration time. Additonal rf pre-amplification can then be used to reduce the integration time.

c. the architecture would be unique in that there would be *no* active electrical components *whatsoever* in the receiver. The only electrical connections required would be the passive waveguiding structures to get the signal to the modulator and a dc bias (which can be supplied remotely). All of the detection electronics can be as far away from the actual antenna/modulator structure as desired, at a sensitivity penalty of the order of 0.8 dB/km (electrical).

d. Given the potential sensitivity it is highly likely that the actual device limitations will be due to spurious scattered light from the carrier. The only way to determine the system limitations will be to construct and characterise a system.

5 CONCLUSIONS

In this paper the possibility of using in-fibre phase gratings for millimetre wave signal distribution and analysis has been discussed. The techniques are essentially wavelength division demultiplexing, however the bandwidths are more closely associated with rf bandwidths rather than optical bandwidths, and as such it is more appropriate to view the structures as rf filters.

A technique for the self-routing of optically generated millimetre wave local oscillator signals to 100 GHz has been proposed. This technique could be useful in millimetre wave ESM systems where distribution of millimetre wave local oscillator power is difficult because of electrical loss, power dissipation or space considerations.

A number of different signal analysis architectures based on in-fibre gratings have been presented, and some broad operational parameters have been established. It would appear that architectures suitable for pulse-to-pulse discrimination are possible that exhibit a sensitivity better than -40 dBm and a dynamic range of at least 40 dB. Channelising architectures that do not require a pulse-to-pulse discrimination ability have the potential for sensitivities in excess of -60 dBm. These figures are based on power into the electro-optic modulator, and do not assume any form of pre-amplification or antenna gain. The system as a whole is unique in that there are no active electronic microwave or millimetre wave components at the receiver whatsoever.

These figures are independent of bandwidth coverage, with the overall system bandwidth being determined by the modulator. Optical modulators with a 52 GHz rf bandwidth and reasonable efficiency are commercially available [8], as are 50 GHz bandwidth amplifiers [11]. There exists significant potential for extending these bandwidths even further into the millimetre wave regime.

Electronic Warfare Division has access to manufacturing facilities for the production of specialised in-fibre gratings through Mr. David Hunter, an EWD cadet working at Sydney University. Mr Hunter's PhD is involved specifically with the signal processing applications of fibre grating structures.

6 REFERENCES

[1] K.O. Hill, Y. Fujii, D.C. Johnson and B.S. Kawasaki, Appl. Phys. Lett. **32**, pg 647, 1978.

[2] W.W. Morey, G. Meltz, G.A. Ball, J.R. Dunphy and F.X. D'Amato, Proc. 17th Aust. Conf. on Opt. Fibre Tech., pp 162-9, 1992.

[3] M.G. Sceats and S.B. Poole, Proc. 16th Aust. Conf. on Opt. Fibre Tech., pp 3502-5, 1991.

[4] G. Meltz and W.W. Morey, SPIE **1516**, Int. Wksp. on Photoinduced Self-Organization Effects in Optical Fiber, pp 185-97, 1991.

[5] L. Goldberg, A.M. Yurek, H.F. Taylor and J.F. Weller, Elect. Lett. **21**, pp 814-5, 1985.

[6] Lightwave Electronics Series 2000 Optical RF Generator Specification Sheet, December 1992.

[7] D.C. Johnson, K.O. Hill, F. Bilodeau and S. Faucher, Elect. Lett. **23**, pp 668-9, 1987.

[8] GEC Marconi TechBrief Issue 1 2-93.

[9] Lasertron Product Guide, 1993.

[10] Opto-electronics Inc. General Catalogue, 1991.

[11] Hewlett-Packard Technical Data Sheet #5091-6246E

THIS PAGE INTENTIONALLY BLANK

DISTRIBUTION

	Number of Copies
DEPARTMENT OF DEFENCE	
Defence Science and Technology Organisation	
Chief Defence Scientist	) 1 shared copy
Central Office Executive	) for circulation
Counsellor Defence Science, London	Doc Control Data Sheet Only
Counsellor Defence Science, Washington	Doc Control Data Sheet Only
Scientific Adviser POLCOM	1
Senior Defence Scientific Adviser	1
Assistant Secretary Scientific Analysis	1
Electronics Research Laboratory	
Director, Electronic Research Laboratory	1
Chief, Communications Division	Doc Control Data Sheet Only
Chief, Information Technology Division	Doc Control Data Sheet Only
Chief, Electronic Warfare Division	1
Research Leader, Secure Communications	1
Research Leader, Signal and Information Processing	1
Research Leader, Electronic Countermeasures	1
Head, Electronic Support Measures Systems Group	1
Head, Electronic Advanced Concepts Group	1
Dr. Anthony C. Lindsay	1
Mr David B. Hunter	1
Navy Office	
Navy Scientific Adviser	1
Army Office	
Scientific Adviser - Army	1
Air Office	
Air Force Scientific Adviser	1
Libraries and Information Services	
Defence Central Library, Technical Reports Centre	1
Manager, Document Exchange Centre (for retention)	1
National Technical Information Service, United States	2
Defence Research Information Centre, United Kingdom	2
Director Scientific Information Services, Canada	1
Ministry of Defence, New Zealand	1
National Library of Australia	1

DISTRIBUTION (cont)

	Number of Copies
Defence Science and Technology Organisation Salisbury, Research Library	2
Library Defence Signals Directorate, Canberra	1
British Library, Document Supply Centre	1
AGPS	1
Spares, DSTOS, Research Library	6

Department of Defence

1. Page Classification
UNCLASSIFIED
2. Privacy Marking/Caveat

DOCUMENT CONTROL DATA SHEET

3a. AR Number	3b. Establishment Number	3c. Type of Report	4. Task Number
AR-008-868	ERL-0827-RR	RESEARCH REPORT	DST 89/116
5. Document Date	6. Cost Code	7. Security Classification	8. No. of Pages: 24
MARCH 1994	230/839256	U | U | U (Document, Title, Abstract)	9. No. of Refs.: 11

10. Title
IN-FIBRE BRAGG GRATINGS FOR MILLIMETRE-WAVE EW SYSTEMS

S (Secret C (Confi) R (Rest) U (Unclass)

* For UNCLASSIFIED docs with a secondary distribution LIMITATION, use (L) in document box.

11. Author(s)

Anthony C. Lindsay

12. Downgrading/ Delimiting Instructions

N/A

13a. Corporate Author and Address

Electronics Research Laboratory
PO Box 1500
SALISBURY SA 5108

14. Officer/Position responsible for

Security SOERL

Downgrading DERL

Approval for release DERL

13b. Task Sponsor

DSTO

15. Secondary Release of this Document

APPROVED FOR PUBLIC RELEASE.

Any enquiries outside stated limitations should be referred through DSTIC, Defence Information Services, Department of Defence, Anzac Park West, Canberra, ACT 2600.

16a. Deliberate Announcement

No limitation.

16b. Casual Announcement (for citation in other documents)

[√] No Limitation [ ] Ref. by Author & Doc No only

17. DEFTEST Descriptors

Photonics, Fiber optics, Electronic warfare, Integrated optics, In-fibre gratings*

18. DISCAT Subject Codes

0905

19. Abstract

Fibre-optic microwave and millimetre wave systems technology has matured rapidly over the last few years. The report examines some possibilities for very wide bandwidth signal distribution and analysis based on in-fibre Bragg gratings. The gratings are fabricated within the fibre core and become integral property of the optical fibre material.

END

FILMED

DATE: 9-94

DTIC